1.0

1.1

1.25   1.4   1.6

2.8   2.5
3.2   2.2
3.6
4.0   2.0

1.8

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A
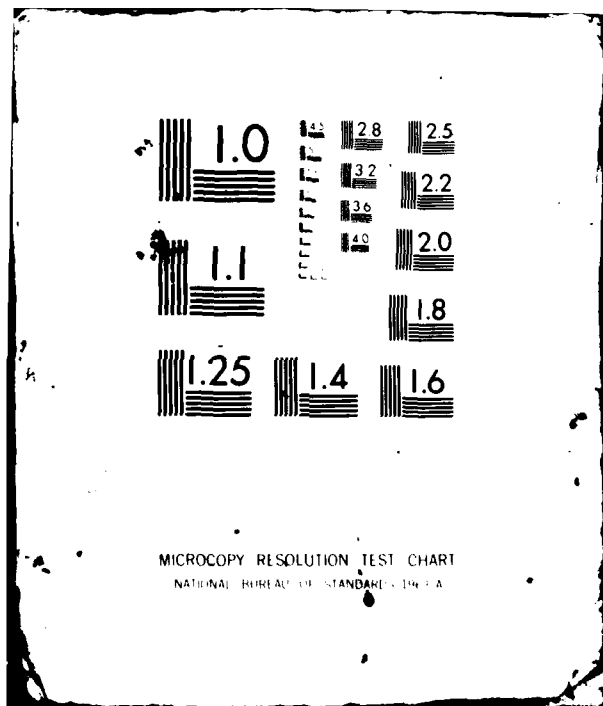
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AUGUST 1979

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HEC CONTRIBUTION TO RESERVOIR SYSTEM OPERATION

by

BILL S. EICHERT
VERNON R. BONNER

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The development, support, and application of HEC computer programs for reservoir system analysis are described. Applications of the programs to many types of reservoir studies are reviewed and referenced.

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HEC CONTRIBUTION TO RESERVOIR SYSTEM OPERATION

by

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HEC CONTRIBUTION TO RESERVOIR SYSTEM OPERATION

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HEC CONTRIBUTION TO RESERVOIR SYSTEM OPERATION[1]
by
Bill S. Eichert[2] and Vernon R. Bonner[3]

INTRODUCTION

This paper describes the role of The Hydrologic Engineering Center
(HEC) of the United States Army Corps of Engineers in developing and
distributing information concerning the use of mathematical models for
reservoir system operations. The paper describes the work of the Center in
this area, and presents background information on the exhibits used by HEC
during the workshop. Exhibits include several wall board displays, a table
display of pertinent HEC publications, a slide-voice cassette on HEC
activities, and a cathode ray tube (CRT) demonstration of HEC capability to
simulate real-time operations of several flood control reservoirs.

The wall board displays include exhibits illustrating HEC's technology
transfer mechanisms (see reference 1) which include videotape distribution
of lectures on Reservoir Analysis; source deck distribution of the generalized
computer programs, Reservoir System Analysis for Conservation (HEC-3) and
Simulation of Flood Control and Conservation Systems (HEC-5); and training
courses in Reservoir System Analysis, Hydropower, and Real-Time Control of
Water Projects. Other wall displays cover descriptions of computer program

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capabilities for HEC-3 and HEC-5 and charts showing reservoir systems where these models have been used. A table display contains samples of various HEC publications concerning reservoir system operation, including training course manuals, technical papers and program manuals. A 35mm slide presentation, with audio cassette, is used to describe the various activities of the Center.

The interactive session on a cathode ray tube terminal demonstrates the results of HEC research in developing techniques for flood forecasting, simulating the reservoir operation and displaying information in tabular and graphical forms for flood control systems. A separate paper, "On-Line Reservoir System Analysis," describes the interactive session. The development, support, and application of HEC reservoir system programs are described in the following sections.

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COMPUTER PROGRAM DEVELOPMENT

The need for comprehensive generalized computer programs for use in planning and operating multipurpose reservoir systems arises from the large investments in manpower and money required to develop separate programs for each system. The cost of a separate computer program for a system would depend upon many factors, but costs of $50,000 to $200,000 would be the approximate range of such special programs. Several generalized programs have been developed for these purposes, including two such programs at HEC. Well-known generalized computer programs for flood forecasting include the National Weather Service models (references 2 and 3), the United States Army Corps of Engineers North Pacific Division (NPD) model called SSARR (reference 4), the Hydrocomp model (reference 5) and the HEC-1 model (reference 6). Well-known simulation models for multipurpose reservoir operation include HEC-3 (references 7 and 8), HEC-5 (reference 9), the NPD SSARR-HYSIS (reference 10) models and the SUPER program (reference 11) which was developed by the Southwestern Division office of the Corps of Engineers.

The initial effort at HEC in reservoir system operation started in 1966 with the development of a monthly multipurpose reservoir operation model (HEC-3) to be used in the planning of reservoir systems including flood control, hydropower and water supply. Numerous basins have been modeled with this program as shown in Table 1 and discussed in the program application part of this paper.

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The development of a generalized model which would handle short-interval system operation required for planning and real-time reservoir operation was started in 1972 with the development of the HEC-5 computer program. The HEC-5 model was constructed so that it could perform monthly operations of multipurpose reservoir systems similar to the HEC-3 model, but which could also simulate short-interval routings (i.e., daily or multi-hourly) and mixtures of the time intervals. Some of the applications of the model are shown in Table 2 and are discussed in the applications section of this paper.

Comparisons of the HEC-3 and HEC-5 reservoir operation models along with the HEC rainfall-runoff model, HEC-1, are shown in Table 3. A brief overview of the capabilities of HEC-1, HEC-3 and HEC-5 are shown in Figures 1-3. Technical procedures used in the models are shown in references 12-14. Training course manuals, which also present technical procedures and program usage, are shown in references 15-17. Other related HEC documents are shown in the publications list, reference 18. Videotapes of various HEC lectures on technical procedures and the use of the computer programs are contained in the HEC videotape catalog (reference 19).

COMPUTER PROGRAM SUPPORT

The Center plays a key role in the dissemination of information
on hydrologic and analytical planning techniques to practicing engineers.
Information is disseminated primarily to Corps offices; however, hundreds
of offices in other U.S. federal and state agencies, and at
universities, consulting engineering firms and foreign governments receive
our programs and publications. The Center uses several methods to disseminate
technical information as discussed in the following paragraphs (also see
HEC Technical Papers 29 and 49).

Source Deck Distribution

As shown in Table 4, the HEC has distributed thousands of source decks
to a variety of different offices. Based on our latest survey in November
1976, over 2,000 source decks are still considered active by the using
offices. Each year approximately 600 new source decks are requested.
Assistance to program users is provided, to the extent possible, in imple-
menting the models on their equipment, answering questions on use of models
and eliminating program malfunctions. These services are provided without
charge except that non-U.S. federal agencies are charged a reproduction
and handling fee for each source deck provided.

Documentation

Computer program documentation is generally accomplished with separate
users (see references 7 and 9) and programmers manuals (see reference 8).
The programmers manual provides useful information for getting the program
running on the users computer, and the users manual explains what the

program does, the technical procedures used, how to code input for the program, and how to interpret output. Notification of program error corrections and improvements is made to all current source deck holders periodically. Other HEC publications include training course manuals, newsletters, professional papers and computer program abstracts. The Center also provides "on-line" information on the two computer systems used by most Corps offices.

Formal Training Courses

Each year, approximately 24 weeks of training are provided by HEC for Corps personnel in 1 to 2-week courses. Approximately 2 to 4 spaces in these courses are reserved for personnel from other U.S. federal, state and university offices. Two special 4-week courses were given to foreign representatives in 1972 and 1974 as a United States contribution to the International Hydrological Decade. HEC course manuals for reservoir systems are contained in references 15-17. Many universities are using HEC-developed training course materials and/or HEC computer models in their courses. Even with the courses now offered, there is insufficient training available to the non-Corps program user.

Videotapes and Instructional Material

Many of the lectures in HEC courses have been videotaped (see reference 19) and the tapes are being loaned out along with instructional material (lecture notes, visual aids and references). These tapes are particularly useful when someone who has taken the course is available to answer questions after the tapes are viewed. Visitors to HEC desiring individual training

on a computer model often use these videotapes before getting individual help on solving a particular problem. Ten visitors from Brazil recently received 4 weeks of training at HEC using this approach.

Publications

Application papers are often prepared as HEC assists various Corps offices in using computer programs in planning and operational studies. Table 5 shows all of the HEC technical papers dealing with reservoir system analysis. Additional information on applications is distributed through HEC courses, training documents (20), and seminars (see references 21, 22).

User Assistance

Other ways of supporting the computer programs besides formal information dissemination vehicles include assisting offices in using the programs when problems arise, making modifications to programs to assist user's needs and developing supplemental software to enhance the use of the programs. Examples include the GETUSGS routines developed to provide USGS daily and monthly flows on computer systems used by the Corps, and a program which develops inflows for the HEC-5 using real-time information on reservoir releases, pool elevations, and river stages.

Personal Contacts

Technology transfer is also greatly enhanced by personal conversations by telephone, by visits to HEC and by HEC personnel attending professional conferences and writing papers.

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COMPUTER PROGRAM APPLICATIONS

Over the years, both HEC-3 and HEC-5 have been applied to many different types of reservoir problems. The applications listed in Tables 1 and 2 and discussed here are limited to those the Center has had a major role. Many of the studies have been presented in the HEC Technical Papers (T.P.) shown in Table 5. The applications outlined here were selected as examples of various types of planning and operational studies.

Yield Potential

The basic procedures for safe yield analysis were presented by Beard in 1965 (T.P. 3). He concluded that the detailed routing studies using historical streamflow sequences was the general procedure used in the United States. The Reservoir Yield Program (reference 23) was released in 1966 to perform multipurpose, single-reservoir yield studies. A demonstration of the advantages of detailed sequential analysis over "short cut" methods is presented in T.P. 14 and an application is shown in the update determination of the Delaware River yield (T.P. 16). A comparison of HEC-3 with the Texas Water Development Board's SIMYLD program is given in T.P. 32 and a comparative study on drought severity and water supply dependability was performed with HEC-3 (T.P. 30).

Storage Requirements

The storage requirement type of study is the complement of the yield study in that the demand is given and the required storage is the unknown. In T.P. 7, the Reservoir Yield Program was used to determine storage

required to meet water quality demands. The HEC-4 program, Monthly Streamflow Simulation (reference 24) was used to estimate the missing monthly flows for the selected study period. A total of 46 sites were evaluated for actual water demands and 10 times those demands. The use and advantages of using simulated streamflow in water yield analysis are presented in T.P. 10.

Reservoir System Expansion

The argument for the use of a generalized reservoir system program for planning and analysis was made by Beard in 1967 (T.P. 4). At that time, HEC-3 had been used in preliminary studies to evaluate the Susquehanna and Willamette River Basins and several smaller systems. Technical Papers 4 and 9 are mainly descriptive of the HEC-3 program capabilities. Application of HEC-3 to the Kanawha River Basin is presented in T.P. 23. The study involved alternative plans with 13 to 18 reservoirs and 16 control points. While most typical project purposes were evaluated in the study, the paper only discusses water quality, reservoir recreation and stream recreation and fishery.

Reservoir system expansion for flood control on the Susquehanna River System was studied using the HEC-5 program (T.P. 44). Technical Paper No. 44 describes the HEC-5 program and the flood control system formulation strategy. The program's capability to compute the Expected Annual Damages from flooding was used to evaluate alternative reservoir systems. An interesting aspect of the study was the sensitivity of the expected annual damages to the system hydrology.

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Hydropower Potential

None of the Technical Papers describes the application of HEC-3 or HEC-5 to the problem of determining the power potential of a site. HEC-3 has been used in several studies (Willamette River Basin in Oregon and Cache and Keetna Projects in Alaska) to determine power potential. The HEC-5 program has been applied to 80 existing reservoirs to automatically determine dependable capacity and firm energy on promising sites determined from the Phase I screening of the National Hydropower Study. Software has been developed to create the input data files for HEC-5, and it is expected to be applied to approximately 2,500 power sites.

Flood Control Measures

Both HEC-1 and HEC-3 have been used for flood control planning. A special version of HEC-1 has the capability to optimally size flood control measures in an urban flood control system (T.P. 42). However, the current flood control reservoir studies are utilizing HEC-5. (T.P. 41 and 43). Training Document No. 7 (reference 20) demonstrates the basic approach used with HEC-5 to perform flood control planning. Measures evaluated include (1) reservoirs, (2) levees or floodwalls, (3) channel modifications, (4) diversions, (5) flood forecasting, (6) flood proofing, (7) relocation, and (8) flood warning. Concepts of system formulation and assessment are also presented.

Power Operations

A major power operation study was performed with HEC-3 on the Arkansas-White-Red River Basins (T.P. 24, 28, 31 and 33). The system consisted of 23 existing or authorized projects, in three river basins, operating in

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an interconnected electrical system. The system operates for flood control, hydroelectric power, water supply, navigation, fish and wildlife, water quality and recreation. The constraints of the many project purposes and legal-institutional constraints made the allocation of system power demands to the 19 power projects a difficult problem. Technical Paper No. 24 describes the model and the system; T.P. 28 describes the system study; T.P. 31 describes rule curve development; and T.P. 33 describes integrated use of hydroelectric and thermal power.

An operating study using HEC-5 to simulate a tandem three-reservoir system with pump-back capability is described in Technical Paper No. 60. The program's system power routine was used to keep the system in balance while meeting downstream minimum flow constraints. The study was made to determine the effects pump-back operation might have on energy production and other project purposes. Simulation results for daily and hourly routings included reservoir areas, elevations and pool fluctuations, as well as energy production data.

Storage Allocation

The allocation of flood control storage in a multiple-purpose project is described in Technical Paper No. 34. The analysis was based on an economic analysis for all purposes in an attempt to derive the economically optimum flood control diagram. The univariate gradient technique (reference 25) in HEC-1 was the optimization procedure employed. The expected value of flood damages was weighed against the economic benefits from conservation storage to determine the "optimum" allocation.

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Flood Control Operations

The application of a reservoir simulation model to real-time flood control operations requires streamflow forecasting, an operation model, and rapid analysis. The development of all three, using HEC-5 as the operation model, is described in T.P. 45. The application of the HEC-5 Flood Damage Calculations to evaluate alternative operation plans is also described. The expected value of annual damages provides a quantitative measure of the benefits from various forecasting and operational schemes.

There have been other studies, as varied as reservoir problems can be. Unfortunately, many of the studies were never described in a complete paper or report. These few examples, however, show the variety of possible applications of generalized simulation models.

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TABLE 1

SYSTEMS SIMULATED BY HEC-3

	River Basin	Location	Reservoirs	Study Purpose
1.	Grand River	South Dakota	46 sites	Screening sites for low flow augmentation
2.	Willamette River	Oregon	14	Hydropower operation study
3.	Cache and Keetna Projects	Alaska	2	Hydropower potential
4.	San Dieguito River	California	4	Operation study
5.	Northeast Water Supply (Connecticut, Hudson, Delaware, Raritan, and Husatonic)	New England	35 plans	Screening sites for water yield
6.	Arkansas-White-Red Rivers	South-Central	23 (19 hydro)	System power analysis
7.	Delaware River	New York	7	Water yield
8.	Chakachatna River	Alaska	-	Hydropower potential
9.	Four River	Florida	15	Water supply and flood control planning
10.	Minnesota River	Minnesota	6	Flood control and low flow analyses
11.	Des Moines River	Iowa	2	Sizing storage
12.	Gila River	New Mexico	1 + water rights	Operation study water supply
13.	Red River of the North	North Dakota Minnesota	10	Planning flood control and conservation
14.	Kanawaha	West Virginia	18 sites	Screening study

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TABLE 2

SYSTEMS SIMULATED BY HEC-5

	River Basin	Location	Number Reservoirs	Number Control Points (including res)	Time Increment (hrs)	Approximate Area (mi^2)
1.	Trinity	Texas	15	28	24	18,000
2.	Merrimack	New England	5	11	3	4,400
3.	Susquehanna	Pennsylvania	34	75	4	24,000
4.	Schuylkill	Pennsylvania	12	26	3	1,900
5.	Potomac	Virginia Maryland Pennsylvania	26	39	2	12,000
6.	Red River of the North	Minnesota	13	29	24 & 720	40,000
7.	Feather	California	3	4	2	5,900
8.	Pajaro	California	3	6	1 & 720	400
9.	Grand (Neosho)	Oklahoma	24	86	2	5,900
10.	James	Virginia	22	35	6	6,800
11.	Red River	Texas Arkansas	14	28	6	12,000
12.	Hudson	New York Pennsylvania	3	5	720	500

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TABLE 2 (cont)

SYSTEMS SIMULATED BY HEC-5

River Basin	Location	Number Reservoirs	Number Control Points (including res)	Time Increment (hrs)	Approximate Area (mi^2)
13. Morova	Yugoslavia	7	14	4	
14. Little River	Oklahoma	4	9	6 & 720	4,100
15. Marshall Fork	Texas	1	2	24	
16. Catskill Aqueduct Hudson River		2	5	720	
17. Sacramento River	California	11	16	2	12,500
18. Shasta-Red Bluff	California	2	5	2	
19. Roaring Fork	Colorado	1	4	24	800
20. San Joaquin	California	22	56	6	14,000
21. Salt River Basin	Arizona	7	12	2 & 720	13,700
22. Savannah Pumped Storage	Georgia	3	5	1 & 24	6,100
23. White River Pumped Storage	Arkansas	3	4	1 & 24 & 720	11,000

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TABLE 3

COMPARISONS OF HEC PROGRAMS
(HEC-1, 3, 5)

Item	HEC-1	HEC-3	HEC-5
1. Determines runoff from rainfall	Yes	No	No
2. Runoff input by incremental local flows	Yes	Yes	Yes
3. Runoff input by cumulative local flows	No	Yes	No
4. Allows period-of-record runs	No	Yes	Yes
5. Allows for individual and group reservoir operation for:			
a. Any configuration system	Yes	Yes	Yes
b. Flood Control			
(1) Routing by linear and nonlinear methods	Yes	No	Yes
(2) Operation for downstream flooding	No	No[1]	Yes
(3) By lagging of flows	No	Yes	Yes
c. Water Supply			
(1) For minimum flows at reservoir	Yes	Yes	Yes
(2) For minimum flows at downstream points	No	Yes	Yes
(3) Diversions	Yes	Yes	Yes
(4) Considers Evaporation	No	Yes	Yes
d. Hydropower (load and head)			
(1) Individual Reservoirs	No	Yes	Yes
(2) Reservoir Systems	No	Yes	Yes
e. Quality Evaluation in Reservoirs			
(1) Non-degradable	No	No[2]	No
(2) Degradable	No	No	No
f. Economic Evaluation			
(1) Flood Control	Yes	No[3]	Yes
(2) Conservation	No	Yes	Hydropower

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[1] Observes flood control constraints for current period with no routing.

[2] Single reservoir conservation program has this ability.

[3] Available for special version (no routing).

TABLE 4

HEC COMPUTER PROGRAM DISTRIBUTION

Program	Program Size		Source Deck Distribution During FY 1978			Mail List Total 2/79
	No. of Statements	Core Storage (Words)	Corps*	Other Govt. Univ. and Foreign	Private	
HEC-1, Flood Hydrograph Package	3,800	62K	1	51	30	473
HEC-2, Water Surface Profiles	9,200	60K	3	78	62	529
HEC-3, Reservoir System Analysis for Conservation	3,700	60K	1	18	6	157
HEC-4, Monthly Streamflow Simulation	2,000	60K	0	20	7	170
HEC-5, Simulation of Flood Control and Conservation Systems	19,200	74K	1	26	9	119
HEC-6, Scour and Deposition in Rivers and Reservoirs	7,000	40K	2	26	7	125
Urban Runoff: Storage, Treatment, and Overflow (STORM)	5,800	50K	2	30	8	274
Flood Flow Frequency Analysis	1,600	15K	1	4	0	31
Gradually Varied Unsteady Flow Profiles	4,300	50K	7	13	8	52
Water Quality for River-Reservoir Systems	15,000	60K	1	18	6	84
All Others	--	--	37	63	51	229
Total	--	--	56	347	194	2,243

*Many Corps offices use HEC-maintained files on central computers.

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TABLE 5

HEC TECHNICAL PAPER SERIES ON RESERVOIR SYSTEMS

Paper No.

3   METHODS FOR DETERMINATION OF SAFE YIELD AND COMPENSATION
WATER FROM STORAGE RESERVOIRS, Leo R. Beard (August 1965)

4   FUNCTIONAL EVALUATION OF A WATER RESOURCES SYSTEM, Leo R. Beard
(January 1967)

7   PILOT STUDY FOR STORAGE REQUIREMENTS FOR LOW FLOW AUGMENTATION,
A. J. Fredrich (April 1968)

9   ECONOMIC EVALUATION OF RESERVOIR SYSTEM ACCOMPLISHMENTS, Leo R.
Beard (May 1968)

10   HYDROLOGIC SIMULATION IN WATER-YIELD ANALYSIS, Leo R. Beard (1964)

14   TECHNIQUES FOR EVALUATING LONG-TERM RESERVOIR YIELDS, A. J. Fredrich
(February 1969)

16   A HYDROLOGIC WATER RESOURCE SYSTEM MODELING TECHNIQUE, L. G. Hulman
(1969)

17   HYDROLOGIC ENGINEERING TECHNIQUES FOR REGIONAL WATER RESOURCE PLAN-
NING, A. J. Fredrich and E. F. Hawkins (October 1969)

23   USES OF SIMULATION IN RIVER BASIN PLANNING, William K. Johnson
and E. T. McGee (August 1970)

24   HYDROELECTRIC POWER ANALYSIS IN RESERVOIR SYSTEMS, A. J. Fredrich
(August 1970)

25   STATUS OF WATER RESOURCE SYSTEMS ANALYSIS, Leo R. Beard (January 1971)

26   SYSTEM RELATIONSHIPS FOR PANAMA CANAL WATER SUPPLY, L. G. Hulman
(April 1971)

27   SYSTEMS ANALYSIS OF THE PANAMA CANAL WATER SUPPLY, D. C. Lewis
and L. R. Beard (April 1971)

28   DIGITAL SIMULATION OF AN EXISTING WATER RESOURCES SYSTEM, A. J.
Fredrich (October 1971)

30   DROUGHT SEVERITY AND WATER SUPPLY DEPENDABILITY, L. R. Beard and
H. E. Kubik (January 1972)

TABLE 5 (cont)

HEC TECHNICAL PAPER SERIES ON RESERVOIR SYSTEMS

FIGURE 1

HEC-1 FLOOD HYDROGRAPH PACKAGE

1. Rainfall-Runoff Model using unit hydrographs or kinematic wave for short-time interval floods.

2. Basin average rainfall from recorders and nonrecorders or given basin average precipitation.

3. Rainfall and snowmelt excess from either simple or complex loss function.

4. Snow accumulation and snowmelt computations for a number of elevation zones within each subbasin.

5. Optimization features for deriving unit hydrograph and loss rate coefficients or stream-routing criteria.

6. Subbasin hydrographs are computed, combined and routed throughout any complex basins which may include reservoirs with simple storage-outflow relationships.

7. Hydrographs are from input historical or design rainfall or based on depth-area-duration data for synthetic floods.

8. Computation of multiflood, multiplan schemes to compute average annual damages of various types at specified damage centers for each plan of development.

9. Determination of effect of tributary reservoir project on floods at downstream locations, without using numerous storm centerings, through stream-system computation.

10. Optimization of components of a flood control system based on minimum cost from flood damages and component costs.

FIGURE 2

HEC-3 RESERVOIR SYSTEM ANALYSIS FOR CONSERVATION

1. Monthly or weekly period Reservoir System (any configuration) Operation simulation assuming no routing (flows are available instantaneously throughout basin).

2. Individual and groups of reservoirs operating for desired targets of water quantity at selected downstream control points based on balancing storages in reservoirs.

3. Groups of reservoirs operating for system power requirements in up to three different power systems.

4. Flood control constraints are observed on monthly or weekly basis.

5. Optimization routines for determining maximum firm yield at a specified downstream control point from specified storages in upstream reservoir or system of reservoirs.

6. Diversions for irrigation or other purposes are allowed at any reservoir or downstream location to any other downstream point in the system or out of the system.

7. Relates hydrologic or physical variables (flow, reservoir storage, hydropower) to economic returns through the use of benefit functions.

FIGURE 3

HEC-5 SIMULATION OF FLOOD CONTROL AND CONSERVATION SYSTEMS

1. Short-interval (and monthly) period multipurpose Reservoir System
    (any configuration) Operation simulator using linear or nonlinear
    channel routing. Also continuous period-of-record analyses possible.

2. Individual and system reservoirs operate to minimize flooding or
    provide low flow at prescribed downstream points and to evacuate flood
    storage as rapidly as possible.

3. Hydropower reservoirs operate for project requirements and/or for
    allocated system energy requirements. Pump-storage operation is also
    available.

4. Optimization routines can size conservation storage or determine
    conservation yield (including hydropower).

5. When there is a choice, selection of reservoirs to release from is
    based on balancing reservoir storages using desired target levels.

6. Diversions (based on given schedules, channel flows or reservoir storages)
    may be made at any location and a portion may be routed and returned at
    any downstream location.

7. Regulated and unregulated flow hydrographs are computed along with
    flooding by reservoirs and total releases from upstream reservoirs.

8. Multiple flood or multiple ratios of a given flood may be computed
    at the same time.

9. Extended duration floods, requiring more core storage than available
    for single flood, are operated automatically as a series of floods
    using the multiple flood option with an overlap between floods to
    maintain continuity.

10. Average annual damages and net system benefits can be calculated for a
    series of alternative systems until best system is found (process requires
    user to select each alternative system).

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TECHNICAL PAPERS

Technical papers are written by the staff of the HEC, sometimes in collaboration with persons from other organizations, for presentation at various conferences, meetings, seminars and other professional gatherings.

Price
$2.00 each

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